

THE X-RAY POSITION AND INFRARED COUNTERPART OF THE ECLIPSING X-RAY PULSAR OAO 1657–415

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ABSTRACT

We have measured the precise position of the 38 s eclipsing X-ray pulsar OAO 1657–415 with the *Chandra X-Ray Observatory*: $\alpha(\text{J2000}) = 17^{\text{h}}00^{\text{m}}48^{\text{s}}90$, $\delta(\text{J2000}) = -41^{\circ}39'21''.6$, error radius = $0''.5$. Based on the previously measured pulsar mass function and X-ray eclipse duration, this 10.4-d high-mass X-ray binary is believed to contain a B supergiant companion. Deep optical imaging of the field did not detect any stars at the *Chandra* source position, setting a limit of $V > 23$. However, near-infrared imaging revealed a relatively bright star ($J = 14.1$, $H = 11.9$, $K_s = 10.7$) coincident with the *Chandra* position, and we identify this star as the infrared counterpart of OAO 1657–415. The infrared colors and magnitudes and the optical non-detections for this star are all consistent with a highly reddened B supergiant ($A_V = 20.4 \pm 1.3$) at a distance of 6.4 ± 1.5 kpc. This implies an X-ray luminosity of 3×10^{36} erg s⁻¹ (2–10 keV). Infrared spectroscopy can verify the spectral type of the companion and measure its radial velocity curve, yielding a neutron star mass measurement.

Subject headings: binaries: close — binaries: eclipsing — pulsars: individual: OAO 1657–415 — stars: neutron

1. INTRODUCTION

Nearly a decade ago, observations with the *Compton/BATSE* all-sky monitor revealed that the 38 s accretion-powered X-ray pulsar OAO 1657–415 ($l = 344^\circ$, $b = 0^\circ.3$) is in a 10.4 d eclipsing binary with an unidentified B supergiant companion (Chakrabarty et al. 1993). The nature of the mass donor was inferred from X-ray timing measurements and the X-ray eclipse duration. Only six other eclipsing X-ray pulsars are known, and all of them yield important constraints on the neutron star mass range (van Kerkwijk, van Paradijs, & Zuiderwijk 1995; Chakrabarty, Psaltis, & Thorsett 2002, in preparation). Although binary radio pulsar data yield more precise neutron star mass measurements (Thorsett & Chakrabarty 1997), the X-ray binaries generally trace a different evolutionary path and therefore may have a systematically different mass range.

OAO 1657–415 is also unique among the known high-mass X-ray binaries in that it appears to occupy a transition region between mass transfer via a stellar wind and Roche-lobe overflow, with possible episodic formation of an accretion disk (Chakrabarty et al. 1993; Bildsten et al. 1997; Baykal 1997, 2000). Since the binary is too wide for Roche lobe overflow to occur, this may provide the first clear evidence that the winds in high-mass X-ray binaries possess sufficient angular momentum to form accretion disks. Identification of the supergiant companion and follow-up spectroscopy would permit both a neutron star mass measurement as well as a search for accretion disk signatures.

However, optical identification has been hampered by the source's poorly known X-ray position. The most precise previ-

ous measurement was derived from a 0.5–4.0 keV *Einstein*/IPC image (Parmar et al. 1980). A reanalysis of these archival data yields R.A. = $17^{\text{h}}00^{\text{m}}47^{\text{s}}70$ and decl. = $-41^{\circ}39'15''.5$ (equinox J2000.0), with a 90%-confidence error radius of $32''$ (Harris et al. 1994). The source is very heavily absorbed ($N_{\text{H}} \sim 10^{23}$ cm⁻²; Polidan et al. 1978; Parmar et al. 1980; Kamata et al. 1990), preventing refined localization with *ROSAT*. Indeed, an 11 ks *ROSAT*/HRI (0.2–2.4 keV) observation failed to detect the source at all (Chakrabarty 1995, unpublished). Previous optical work has shown that there are no OB supergiants in the *Einstein* error circle with magnitude $V < 19$ (Roche 1993; Maxwell, Norton, & Roche 2001), indicating that the luminous optical counterpart is also subject to heavy extinction.

In this Letter, we report a precise position measurement of OAO 1657–415 using the *Chandra X-Ray Observatory* and the identification of an infrared counterpart, presumably an OB supergiant. We discuss our imaging observations (X-ray, optical, and infrared) in §2, our X-ray spectroscopy in §3, and the implications of our observations in §4.

2. X-RAY AND OPTICAL/IR IMAGING

We observed OAO 1657–415 with *Chandra* on 2001 February 10 for 5.1 ks using the High Energy Transmission Grating Spectrometer (HETGS) and the spectroscopy array of the Advanced CCD Imaging Spectrometer (ACIS-S). The HETGS employs two sets of transmission gratings: the Medium Energy Gratings (MEGs; 0.4–5.0 keV) and the High Energy Gratings (HEGs; 0.8–10.0 keV). The HETGS spectra were imaged by ACIS-S, an array of six CCD detectors. The HETGS/ACIS-S combination provides an undispersed (zeroth-order) image

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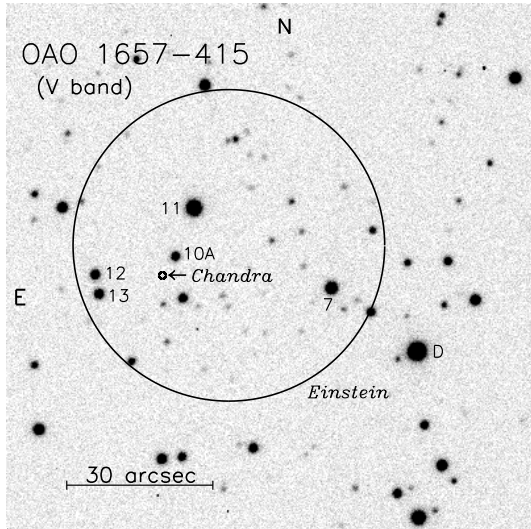


FIG. 1.— V-band finder for the OAO 1657–415 field. The $32''$ Einstein error circle and the $0''.5$ Chandra error circle are indicated. No star is detected at the Chandra position down to a limiting magnitude of 23.1. For reference, several field stars are labeled using the numbering scheme of Roche (1993). Star D of Maxwell et al. (2001) is also noted.

and dispersed spectra from the gratings. The various orders overlap and are sorted using the intrinsic energy resolution of the ACIS CCDs, which are read out every 3.2 s. Pulsations were detected from OAO 1657–415 at a barycentered period of 37.329 ± 0.020 s (epoch MJD 51950.84), verifying that the detected source is the pulsar. Besides the pulsar, no other X-ray sources are detected in the Chandra image.

The zeroth order HETGS image of OAO 1657–415 was affected by photon pileup (see, e.g., Davis 2001), but not so severely as to distort the image centroid. We measured the source position with the CIAO tool *celldetect*.⁴ Our best-fit position was R.A. = $17^{\text{h}}00^{\text{m}}48^{\text{s}}.90$ and decl. = $-41^{\circ}39'21''.6$ (equinox J2000.0), with an approximate error radius of $0''.5$ (Aldcroft et al. 2000⁵). This position lies within the $32''$ Einstein error circle but is $15''$ from its center. The Chandra position excludes the candidate optical counterpart suggested by Maxwell, Norton, & Roche (2001; star D in Figure 1), which lies $55''$ away.

We obtained deep *UBV*-band optical images of the OAO 1657–415 field on 1999 August 8 using the EMMI camera at the f/11 Nasmyth B focus of the 3.5-m New Technology Telescope (NTT) at the European Southern Observatory (ESO) at Cerro La Silla, Chile. These observations were made through the NTT service observing program. We derived an astrometric solution for these images by matching 21 field stars to the USNO-A2.0 catalog of astrometric standards (Monet et al. 1998). The rms error in the positions was $0''.25$. Applying this solution, we found no stars at the Chandra position for OAO 1657–415. Limits on the brightness of the optical counterpart are given in Table 1. The flux calibration of these images was done by comparison with observations of photometric standards (Landolt 1992). We show a *V* image of the field in Figure 1

More recently, we obtained *JHK_s* near-infrared images of the

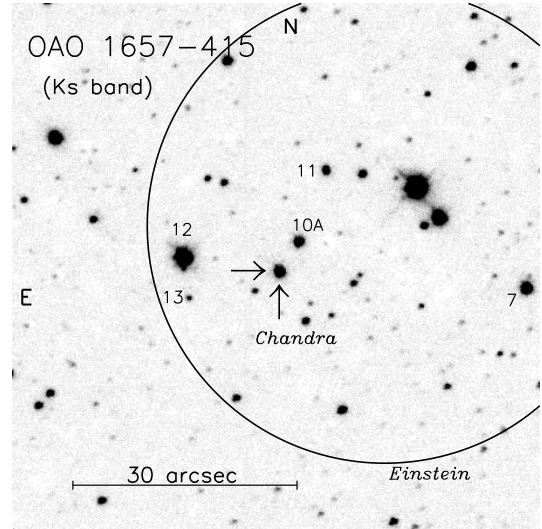


FIG. 2.— *K_s*-band finder for the OAO 1657–415 field. The infrared counterpart is indicated by the arrows. For reference, the $32''$ Einstein error circle is shown and several of the field stars are labeled as in Figure 2. Some of the bright field stars in the *K_s* image are undetected in the *V* image, indicating how heavily absorbed this field is.

field on 2002 February 25 using the Ohio State Infrared Imager/Spectrometer (OSIRIS) at the f/14 tip-tilt focus of the 4-m Blanco Telescope at the Cerro Tololo Inter-American Observatory (CTIO) in Chile. We derived an astrometric solution for these images by matching 12 stars in the *K_s* image with the *V* image described above. (The field of view was too small to allow a direct tie to the USNO-A2.0 catalog.) The rms error in the positions was dominated by the optical fit errors. Using this solution, we found a relatively bright star within $0''.1$ of the Chandra position; within the position uncertainties, these positions are coincident, and we identify this star as the infrared counterpart of OAO 1657–415. (This object is called star 10B in the infrared images of Roche 1993.) A *K_s* image of the field is shown in Figure 2. We flux-calibrated our infrared images by comparison with observations of photometric standards at various airmasses (Persson et al. 1998). The measured *JHK_s* magnitudes are given in Table 1, and are similar to those measured by Roche (1993).

3. X-RAY SPECTROSCOPY

Our short Chandra/HETGS observation also yielded an X-ray spectrum. The combined \pm first-order dispersed MEG and HEG spectra were extracted and simultaneously fitted to an absorbed power-law + gaussian model. The observed HEG count spectrum is shown in Figure 3. Very few counts were detected below 4 keV due to the large hydrogen column density of $N_{\text{H}} \approx 4 \times 10^{23} \text{ cm}^{-2}$ found by fitting the absorption model to the spectra. The power-law index and normalization are poorly determined due to the limited energy range available for fitting (3.5–9.0 keV). An Fe *K α* emission line is clearly detected at 6.4 keV, with flux $\approx 8 \times 10^{-4} \text{ photon cm}^{-2} \text{ s}^{-1}$ and equivalent width $\approx 111 \text{ eV}$ (we do not quote formal uncertainties, as the line strength is poorly constrained due to the large uncertainty

⁴ See <http://cxc.harvard.edu/ciao>.

⁵ See also <http://cxc.harvard.edu/cal/ASPECT/celmon/>.

TABLE 1
OPTICAL/IR PHOTOMETRY OF OAO 1657–415

Band	Wavelength	Magnitude	Obs./Date
<i>U</i>	3600 Å	>23.7 (3 σ)	ESO, 1999 Aug 8
<i>B</i>	4400 Å	>24.0 (3 σ)	ESO, 1999 Aug 8
<i>V</i>	5500 Å	>23.1 (3 σ)	ESO, 1999 Aug 8
<i>J</i>	1.1 μ m	14.08 \pm 0.11	CTIO, 2002 Feb 25
<i>H</i>	1.6 μ m	11.93 \pm 0.10	CTIO, 2002 Feb 25
<i>K_s</i>	2.14 μ m	10.67 \pm 0.11	CTIO, 2002 Feb 25

in the continuum level). Additionally, we detect the Fe K photoelectric absorption edge near 7.1 keV. Based on the strength of this edge, we estimate an optical depth $\tau \sim 1.2$ which implies an even higher hydrogen column density of $N_H \sim 10^{24} \text{ cm}^{-2}$ for the solar abundance values of Wilms, Allen, & McCray (2000). However, given the limited statistics of our short observation, this discrepancy is not serious. The total observed flux (which is not sensitive to the detailed spectral model) was $1.9 \times 10^{-10} \text{ erg cm}^{-2} \text{ s}^{-1}$ (2–10 keV). For photon index $\Gamma = 1$, this corresponds to an unabsorbed flux of $6.4 \times 10^{-10} \text{ erg cm}^{-2} \text{ s}^{-1}$ (2–10 keV).

4. DISCUSSION

We have precisely measured the X-ray position of OAO 1657–415 and have identified its infrared counterpart. Based on the X-ray pulsar’s orbital parameters and the duration of the X-ray eclipse, Chakrabarty et al. (1993) deduced that the mass donor in this binary has a mass of 14–18 M_\odot and a radius of 25–32 R_\odot , corresponding to a B0–6 supergiant. They additionally estimated that the source distance is $\gtrsim 11$ kpc using the pulsar’s accretion torque behavior. We can compare these predictions with the observed properties of the counterpart. The intrinsic infrared colors of a B0–6 supergiant are $J-H = -0.02 \pm 0.04$ and $H-K = -0.04 \pm 0.04$ (Whittet & van Breda 1980). Using the interstellar reddening relation of Rieke & Lebofsky (1985), the observed colors imply a very large reddening of $A_V = 20.4 \pm 1.3$.

We can also estimate the source distance. For the inferred mass and radius range, the companion should have a luminosity of $\log(L/L_\odot) = 4.8 \pm 0.2$ and a temperature of $\log T = 4.28 \pm 0.08$ (Maeder & Meynet 1989). Applying the appropriate bolometric corrections (e.g., Drilling & Landolt 2000), the expected absolute visual magnitude of the star is $M_V = -6.0 \pm 0.2$. From the intrinsic B supergiant color $V-J = -0.3 \pm 0.2$ (Whittet & van Breda 1980) and our observed J magnitude, we thus derive a source distance of $D = 6.4 \pm 1.5$ kpc, somewhat closer than estimated from the X-ray pulsar’s spin-up rate. The H and K_s magnitudes yield very similar distance values. The observed optical limits are also consistent with our derived reddening and distance.

Thus, we conclude that the photometric properties of the infrared counterpart are consistent with the B supergiant companion predicted by Chakrabarty et al. (1993). We note, however, that the infrared photometry alone cannot reliably provide a spectral classification for the companion, since the reddening and spectral type are degenerate on an infrared color-color diagram. However, infrared spectroscopy can provide an accurate spectral classification of the counterpart (Hanson, Conti, & Rieke 1996; Blum et al. 1997; Wallace et al. 2000) and should eventually allow a radial velocity curve to be measured. This

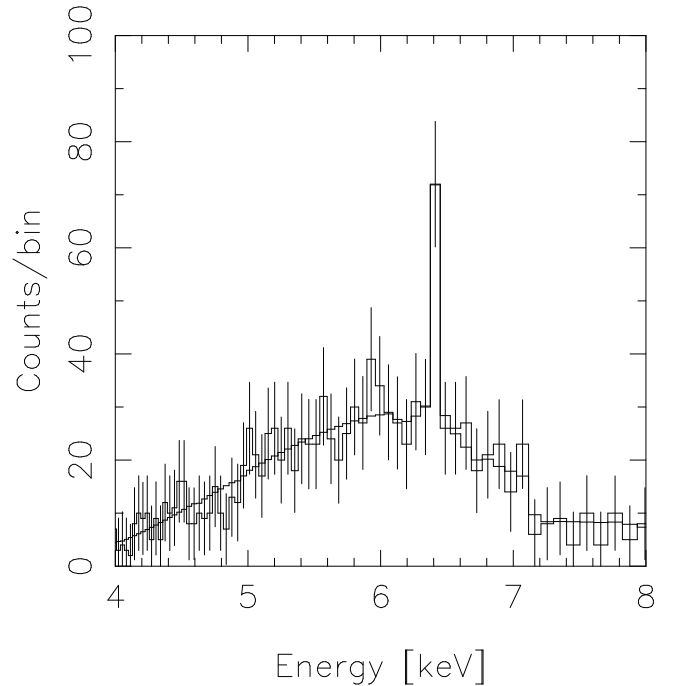


FIG. 3.— X-ray count spectrum of OAO 1657–415 from *Chandra*/HETGS/HEG. The absorbed power-law spectral model shown has $N_H = 4.1 \times 10^{23} \text{ cm}^{-2}$, photon index $\Gamma = 1.0$, and normalization 0.046 photon $\text{cm}^{-2} \text{ s}^{-1} \text{ keV}^{-1}$ at 1 keV. An Fe K emission line at 6.4 keV and an Fe K absorption edge near 7.1 keV are clearly visible.

will yield the seventh dynamical measurement of the neutron star mass in an X-ray binary.

Our X-ray spectral measurements indicate that OAO 1657–415 is extremely absorbed. However, though the optical extinction is also large, it is an order of magnitude smaller than would be inferred from the usual Galactic ratio of $N_H/A_V = 1.8 \times 10^{21} \text{ cm}^{-2} \text{ mag}^{-1}$ (Predehl & Schmitt 1995). This probably indicates that most of the X-ray absorption is by gas local to the binary, presumably fed by the companion’s stellar wind, and that this gas has a very low dust content (as expected for a B star wind). The same phenomenon has been observed in the well-known wind-fed X-ray pulsar Vela X-1 (Sako et al. 1999). Indeed, OAO 1657–415 and Vela X-1 ($d = 1.9$ kpc) are very similar in most respects. Both pulsars are in eclipsing high-mass X-ray binaries containing a B supergiant companion, have similar orbital parameters, are accreting from their companion’s stellar wind, and have similar X-ray luminosities (for our derived distance, the 2–10 keV luminosity of OAO 1657–415 is $3 \times 10^{36} \text{ erg s}^{-1}$). Thus, we expect that OAO 1657–415 should be a good candidate for studying the ionized stellar wind of the B supergiant with X-ray line spectroscopy, as has been done with Vela X-1 (Sako et al. 1999; Schulz et al. 2002).

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